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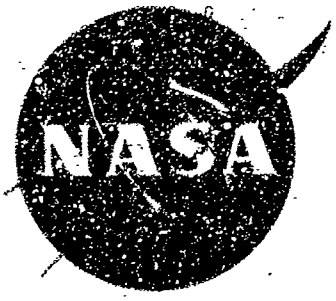

NASA CR-66878

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PLANETARY ENVIRONMENT SIMULATION

Erosion And Dust Coating Effects

By G.L. Adlon, E.L. Rusert, and T.H. Allen

Prepared by

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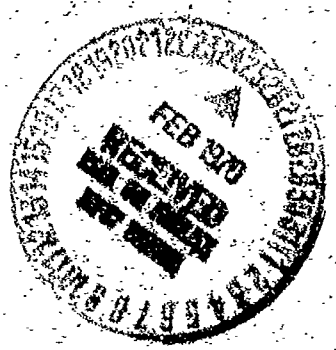

for Langley Research Center

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PLANETARY ENVIRONMENT SIMULATION

Erosion And Dust Coating Effects

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G.L. Adlon, E.L. Rusert, and T.H. Allen

Prepared under Contract No. NAS 1-8708

MCDONNELL DOUGLAS ASTRONAUTICS COMPANY
EASTERN DIVISION
ST. LOUIS, MISSOURI

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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1. SUMMARY

The purpose of Task III of NASA Contract No. NAS1-8706, was to study the effects of sand/dust erosion on candidate thermal control coatings, optical windows, and mirrors for the proposed 1973 Mars Viking Lander.

The specific objectives were to determine changes in the following parameters as a result of exposure to the erosion environment:

- Coating thickness.
- Coating weight.
- Solar absorptance of coatings.
- Infrared emittance of coatings.
- Transmittance for optical windows.
- Reflectance for optical mirrors.

All objectives of Task III were successfully completed. Martian sand/dust storm erosion conditions were simulated by airborne silica sand particles in wind at velocities of 220 ft/sec using air at a static pressure of 7 torr. Large increases in solar absorptance were measured for the majority of the coatings exposed to the simulated environment. The hard materials (flame sprayed coatings and glass reference slides) and the soft alumino-silicate pigmented glass resin coating experienced the greatest coating weight loss. Tests conducted to determine the extent of degradation of optical surfaces indicated that optical windows exposed for longer than 10 minutes and optical mirrors exposed for longer than 5 minutes were significantly degraded.

2. INTRODUCTION

There has been considerable discussion in recent years about the possibility of Earth-type sand/dust storms occurring on the Martian surface. The belief in such storms has been strengthened by some of the data acquired by Mariner probes and Earth-based telescopic observations. These data covered parameters such as surface pressures, temperature variations, and surface features.

McDonnell Douglas utilized these data as the criteria for simulation of surface winds and subsequent analyses of phenomena which might be caused by the winds. McDonnell Douglas then experimentally verified the possibility of occurrence of sand/dust storms on Mars. This experimental capability was extended to include studies of erosion of typical candidate materials for use on the exterior of a Mars planetary larder.

One of the major goals of the Viking project is to land a vehicle containing a scientific package on the surface of Mars in 1973. The vehicle will be required to perform scientific experiments for a period of 90 days in an environment which is considered to be quite hostile because of the low surface pressure and extreme temperature variations which make the generation of high velocity winds theoretically possible.

This report presents the results of a series of tests performed under simulated Martian sand/dust storm conditions which provide data on the combined influence of wind velocity, sand/dust density*, and atmospheric pressure on the thermal radiation or optical properties of selected thermal control coatings and

* In this report, "sand/dust density" refers to the mass of airborne sand and dust per unit volume of air in the simulated Martian wind. The term "particle density" is also used in this context.

optical materials. Erosion rates, thermal radiative properties, and/or optical properties were determined for twelve types of thermal control coatings, two types of mirrors, and two types of window materials.

Volume II of the Final Report on Contract No. NAS1-8706 is designated as NAS CR-66882, "Planetary Environment Simulation, Martian Sand and Dust Storm Simulation and Evaluation."

3. PROBLEM DEFINITION AND APPROACH

Studies by others have established some probable Martian environmental conditions based on telescopic observations supplemented with postulations of related surface phenomena.[1,2] Conclusions have also been drawn from data obtained during the Mariner IV flyby to help establish Mars surface conditions to be simulated.[3,4,5] Mariner IV measurements allowed determination of atmospheric pressure and temperature.

The Martian surface may contain much silicate material, based on analogies between Earth and Lunar surface characteristics and measurement of Martian surface phenomena.[4] Conclusions drawn about surface roughness and particle size distribution on Mars are based upon some Earth-type geological processes.

The wind velocities required to create sand/dust storms under Martian conditions must be approximately nine times those required on Earth, based on threshold velocity equations developed for Earth sand/dust storms.[5] The fact that portions of the Martian surface are occasionally obscured by what appear to be transient white, blue, or yellow cloud formations implies the existence of wind patterns there.

McDonnell Douglas became concerned with the possible effects of sand/dust storms on planetary lander materials during the early stages of the Voyager proposal effort.[6] The simulated Martian environments generated at McDonnell Douglas then were quite similar to the parameters listed more recently by NASA.[1]

Those early tests confirmed the hypothesis that simulated Martian sand/dust particle transport and wind characteristics are similar to those on Earth, except for the higher wind velocities and lower pressures on Mars. It was realized that further studies of the mechanism of particle transport by low-

pressure wind was required and the recent investigations performed in this area are described in Volume II of this report.

The relationship between the atmospheric pressure and the wind velocity required to cause particle movement on the surface is expressed by the following equation:

$$P_d = \gamma V^2/2g$$

where,

P_d = dynamic pressure (lb_f/ft^2)

γ = atmospheric density (lb_m/ft^3)

V = fluid threshold velocity (ft/sec)

g = unit conversion factor ($32.17 \frac{ft\ lb_m}{lb_f\ sec^2}$)

The test samples selected for evaluation are listed in Table 1. Earlier studies had shown that the erosion resistance of pigmented thermal control coatings is controlled by the binder in the coating formulation, so representative coatings were chosen for these tests on the basis of their binders. These binders included Owens, Illinois No. 650 silicone resin, General Electric RTV-602 methyl silicone, DeSoto 529-004 epoxy, and DeSoto 821-010 polyurethane. The major requirement for a thermal control coating on the lander will be for a high thermal emittance (ϵ_T) low solar absorptance (α_S) radiator coating which will maintain its low α_S/ϵ_T ratio even after partial erosion. It should be possible to formulate other coatings with the binders which have been evaluated but with pigments chosen to optimize the radiative properties desired. Some of

Table 1 Test Specimens

Specimen Group	Part No.	Quantity	Supplier	Specimen Base Material	Type	Finish Source	Finish Base Material
Thermal Control Coatings	C-1A, 1B, 1C, 1D	4	McDonnell	Alum 6061-T6 QQ-A-250 11 .063 Thick	Aluminized Teflon FEP Type 5 Mil Thick	G.T. Schjeldahl Company	N A
	C-2A, 2B, 2C, 2D	4	McDonnell JPL	Alum 6061-T6 QQ-A-250 11 .063 Thick	Teflon Gold Coating Teflon Type A FEP 2 Mils Thick	JPL	G.E. RTV 615 Adhesive
	C-3A, 3B, 3C, 3D	4	McDonnell	Alum 6061-T6 QQ-A-250 11 .063 Thick	Kapton Gold Coating 5 Mil Thick Kapton	JPL	G.E. RTV 615 Adhesive
	C-4A, 4B, 4C, 4D	4	McDonnell	Alum 6061-T6 QQ-A-250 11 .063 Thick	Grit Blast With #220 Grit AL_2O_3	McDonnell	N A
	C-5A, 5B, 5C, 5D	4	McDonnell	Alclad Alum QQ-A-250 5 .063 Thick	Glass Resin 1.5 Mils Thick Owens Illinois No. 650 Unpigmented	McDonnell	N A
	C-6A, 6B, 6C, 6D	4	McDonnell	Alum 6061-T6 QQ-A-250 11 .063 Thick	White Polyurethane 2.6 Mils Thick DeSoto Inc. No. 821-010	McDonnell	N A
	C-7A, 7B, 7C, 7D	4	McDonnell	Alum 6061-T6 QQ-A-250 11 .063 Thick	Alum Pigmented Silicone 7 Mils Thick	McDonnell	Prime Surface with G E. RTV 602 Silicone
	C-8A, 8B, 8C, 8D	4	McDonnell	Alum 6061-T6 QQ-A-250 11 .063 Thick	Alum Pigmented Epoxy 5 Mils Thick DeSoto Inc. No. 529-004	McDonnell	N A
	C-9A, 9B, 9C, 9D	4	Hughes Aircraft	Alum 6061-T6 QQ-A-250 11 .063 Thick	Alumino - Silicate Pigmented Glass Resin (H-10) 13 Mils Thick	Hughes Aircraft	N A

(Continued)

Table 1 Test Specimens (Continued)

Specimen Group	Part No.	Quantity	Supplier	Specimen Base Material	Type	Finish Source	Finish-Base Material
Thermal Control Coatings	C-10A, 10B, 10C, 10D	4	NASA-Langley	Alum 6061-T6 QQ-A-250/11 .063 Thick	Flame Sprayed Nickel Aluminide (NiAl) 7 Mils Thick METCO No. 404	NASA-Langley	N/A
	C11A, 11B, 11C, 11D	4	NASA-Langley	Alum 6061-T6 QQ-A-250/11 .063 Thick	Flame Sprayed NiAl (40%) + ZrO_2 (Zirconia) (60%) 7 Mils Thick METCO No. 413	NASA-Langley	N/A
	C-12A, 12B, 12C, 12D	4	NASA-Langley	Alum 6061-T6 QQ-A-250/11 .063 Thick	Plasma Sprayed AL_2O_3 16 Mils Thick METCO No. 101	NASA-Langley	N/A
Windows	W-1A, 1B, 1C, 1D	4	McDonnell/ Corning Glass	Fused Silica 0.25 Thick Corning No. 7940	Polish One Side To 1/4 Wavelength Flatness Wedge Angle < 30 Sec	McDonnell	
Windows	W-2A, 2B, 2C, 2D	4	McDonnell Corning Glass	Alumino-Silicate 0.25 Thick Corning No. 1723	Polish One Side To 1/4 Wavelength Flatness Wedge Angle < 30 Sec	McDonnell	
Mirrors	M-1A, 1B, 1C, 1D	4	McDonnell/ Liberty Mirror	Soda Lime 0.25 Thick	Aluminized Front Surface (Over-Coat With SiO_2)	McDonnell	
Mirrors	M-2A, 2B, 2C, 2D	4	McDonnell/ Corning Glass	Fused Silica .125 Thick	Aluminized Back Surface (Overcoat with SiO_2	McDonnell	G.E. No. 151 Silica
Reference	R-1 To R-9	9	McDonnell	Microscope Glass Slides	Standard Slide Surface Finish	McDonnell	
Reference	R-1 To R-9	9	McDonnell	Alum 6061-T6 QQ-A-250/11 .063 Thick	Grit Blast With #220 Grit AL_2O_3	McDonnell	
Reference	R-1 To R-9	9	McDonnell	Alum 6061-T6 QQ-A-250/11 .063 Thick	Plasma Sprayed AL_2O_3 METCO #101	McDonnell	

the metallized polymeric films and flame or plasma sprayed coatings were also known to possess high α_T and low σ_S, and were included in the test program. These coatings included aluminum and gold-metallized Teflon, gold metallized Kapton, and plasma sprayed aluminum oxide (Al_2O_3).

The optical materials chosen were fused silica (Corning 7940) and aluminosilicate (Corning 1723), a first surface aluminized mirror with SiO_2 coating, and a second surface aluminized fused silica mirror. These materials were considered to be typical candidate materials for use in camera optical systems.

Wind velocity, static air pressure, and sand density for the test were selected by NASA and McDonnell Douglas on the basis of the Mars engineering model parameters.[1] Silica sand particles ranging from 44 to 105 microns were used for all tests. These particle sizes were within the range postulated to occur on the Martian surface. Particle screening was performed in accordance with MIL-STD-810A. The particle density used in tests was based upon results of studies of particle saltation phenomena in simulated Martian sand storms and was controlled by regulating the sand feed rate into the supply air stream. The effect of the velocity, pressure and sand density was evaluated by measuring the erosion of selected reference specimens of grit blasted aluminum, plasma sprayed Al_2O_3, and glass microscope slides prior to exposing the test samples listed in Table 1.

4. TEST METHODS AND RESULTS

4.1 TEST FACILITY

4.1.1 ENVIRONMENTAL CHAMBER. The previous coating erosion study which was referenced in this report was performed in the same wind tunnel system used in this study.[6] However, in the previous experiments, the tunnel was located in a 14 x 14 x 35-foot high-altitude chamber with a 3-stage steam ejector pumping system.[2] Because of schedule conflicts with another test program in that chamber, the wind tunnel and associated simulator equipment were relocated in a 9 x 11 x 20-foot high-altitude chamber with a six-stage steam ejector pumping system. The steam ejector is a noncondensing unit which uses 65,000 pounds of steam per hour and has the performance, measured at the chamber, shown in Figure 1. The wind tunnel system includes an air disperser, stilling screen, and convergent nozzle (Figure 2). The complete system is capable of simulating the required Mars engineering model parameters,[1] and can be used to generate winds up to 550 ft/sec through the 9.5 x 14.5-inch tunnel exit plane at a chamber static pressure of 6 torr.

The chamber is connected to the steam ejector by a 30-inch diameter pipeline with a butterfly valve used to control chamber pressure and to isolate the ejector from the chamber during ejector startup and shutdown. Variations in the combination of wind velocity and chamber pressure are achieved by adjusting the metered air flow to the tunnel and by throttling the exhaust flow with the butterfly valve. Air used in the wind tunnel is drawn from the McDonnell Douglas supersonic wind tunnel air storage tanks. This air is filtered and dried to a dew point of -20 to -40°F. The air is metered through an orifice type flowmeter.

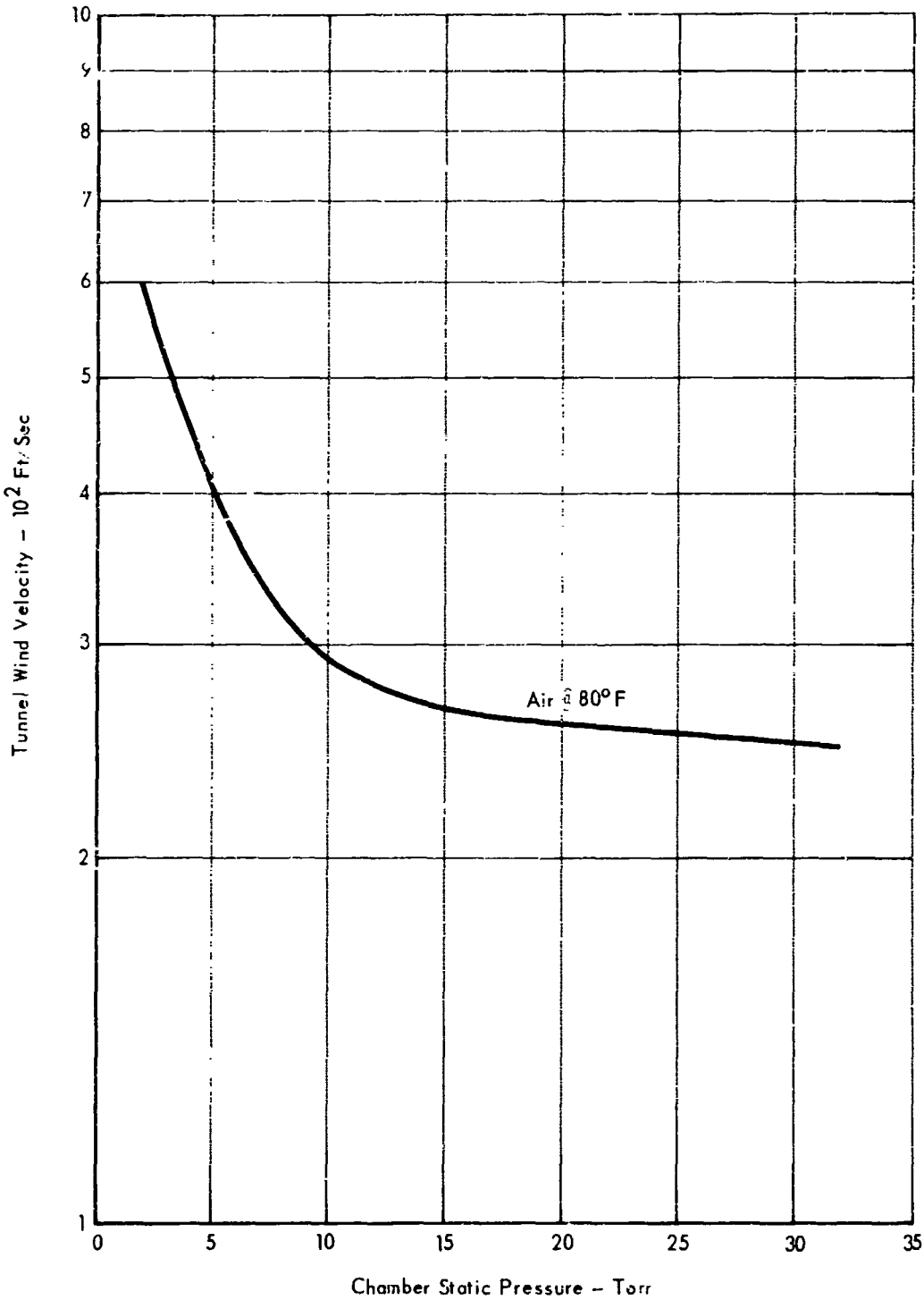


Figure 1 Steam Ejector Performance With 9.5 In. x 14.5 In. Tunnel In 11-Ft Chamber

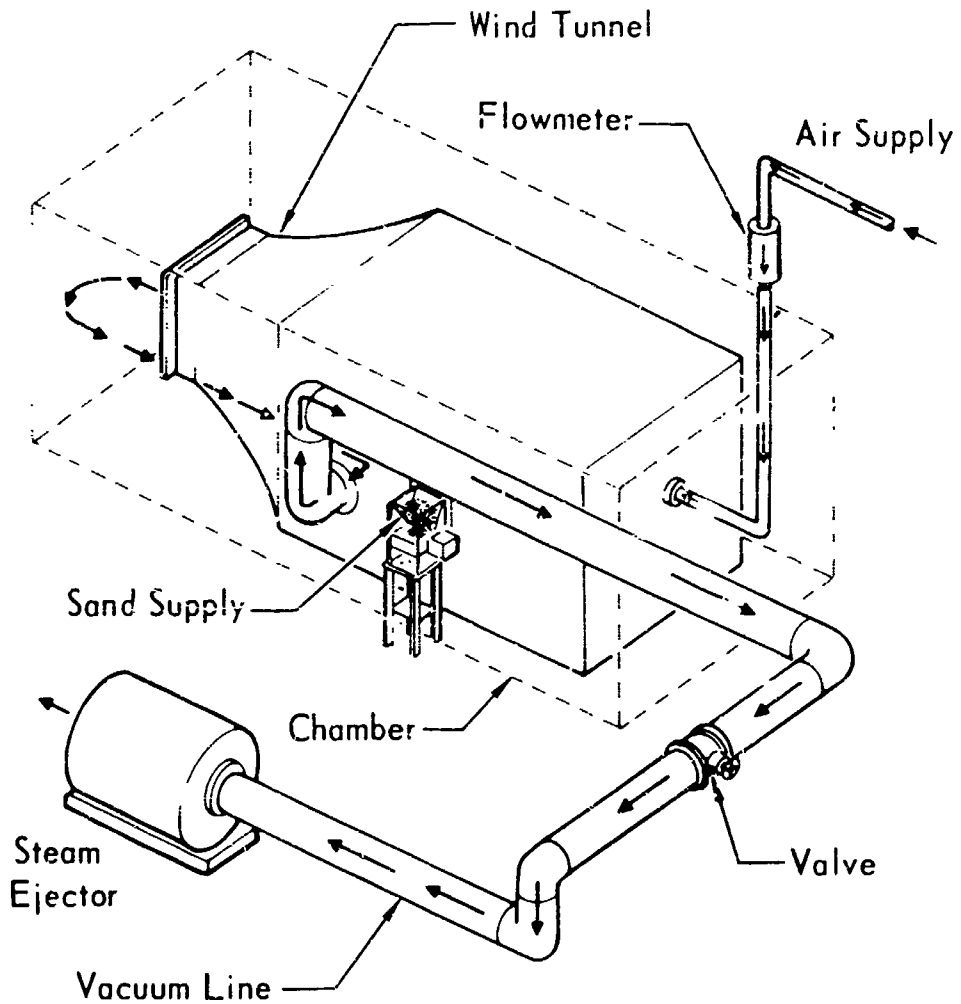


Figure 2 – Martian Environmental Test Facility

Downstream from the flowmeter, the air flows through a 2-inch diameter pipe to a disperser inside the tunnel, through the stilling screens, through the 9.5 x 14.5-inch nozzle, and into the chamber.

4.1.2 SAND METERING SYSTEM. The silica sand used in the erosion tests was metered into the 2-inch pipeline at a point between the flowmeter and disperser. The sand metering system was set to produce a particle density of 2×10^{-4} oz/ft^3 at the tunnel outlet, with a wind velocity of 220 ft/sec and a chamber pressure of 7 torr. The sand metering system consists of a hopper with a variable-size orifice at the bottom through which sand is gravity-fed onto a curved endless belt driven by a variable speed motor (Figure 3). The belt, which passes under a scraper blade to level the sand surface, carries a known volume of sand per unit length, and is driven at a speed to suit the sand density requirements of the test. Sand drops off the end of the belt into a funnel which is connected to the 2-inch air line leading into the wind tunnel. The higher atmospheric pressure outside the line carries the sand from the funnel into the low pressure air stream.

4.1.3 TEST SPECIMEN FIXTURE. To more efficiently utilize facility operating time in testing multiple samples, a specimen holder assembly was fabricated which includes six specimen holders mounted on a remote-controlled stepper motor shaft. Each specimen holder can hold five 2 x 2-inch coating specimens, which permits testing of as many as 30 different specimens without interrupting operation of the simulator. The assembly was located at the exit of the tunnel (Figure 4). The six holders are contained within a housing so that only one holder at a time is exposed to the wind. Each holder can be set to any desired angle relative to the wind stream.

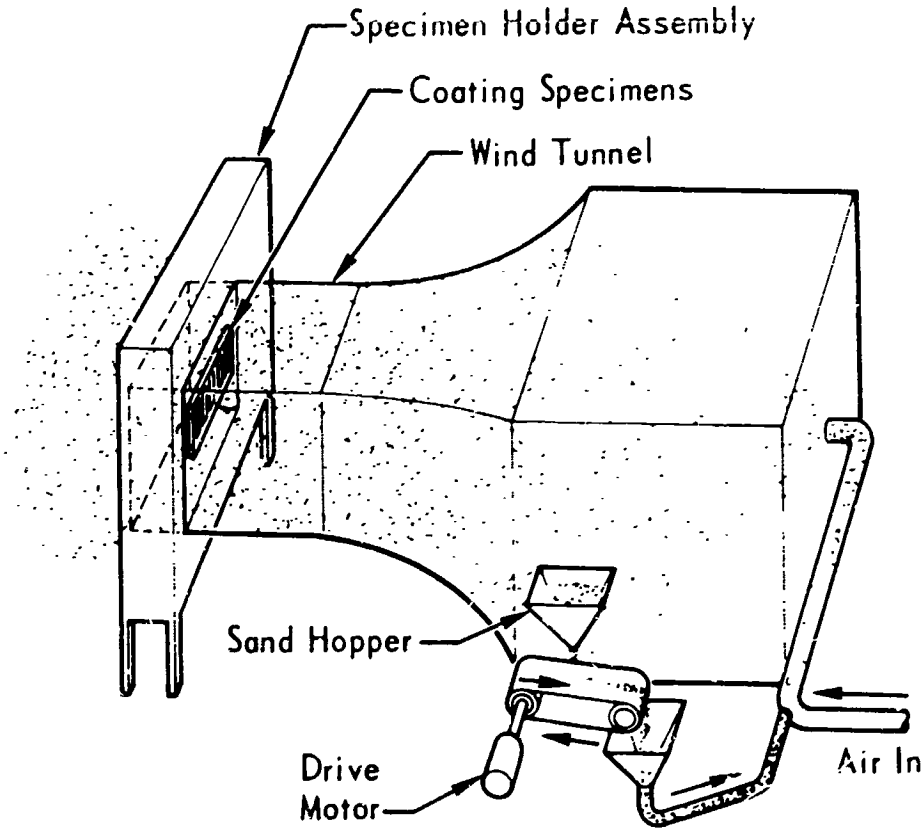
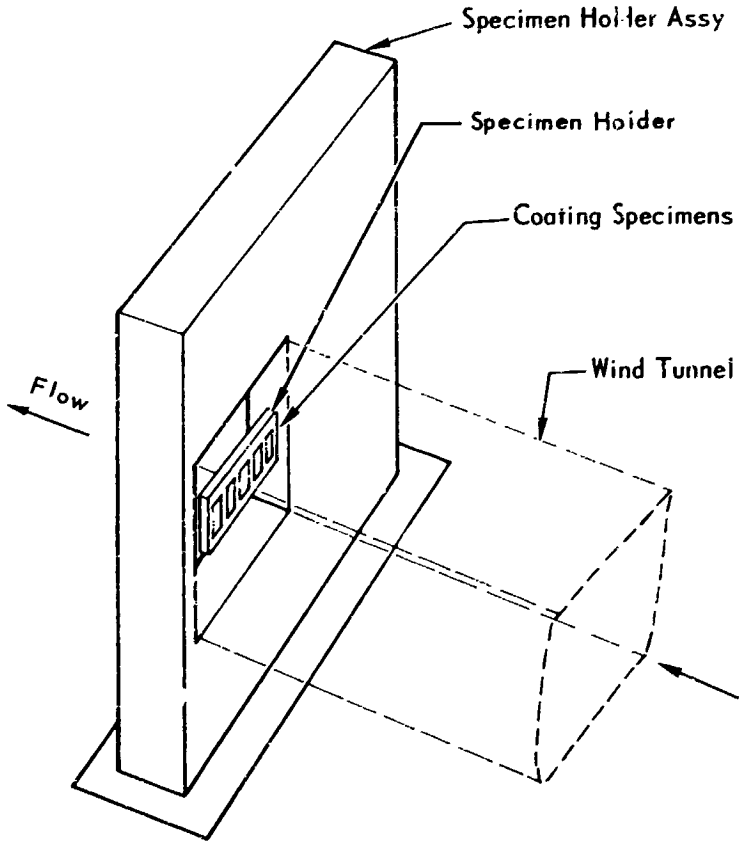


Figure 3 – Wind Tunnel and Sand Metering System



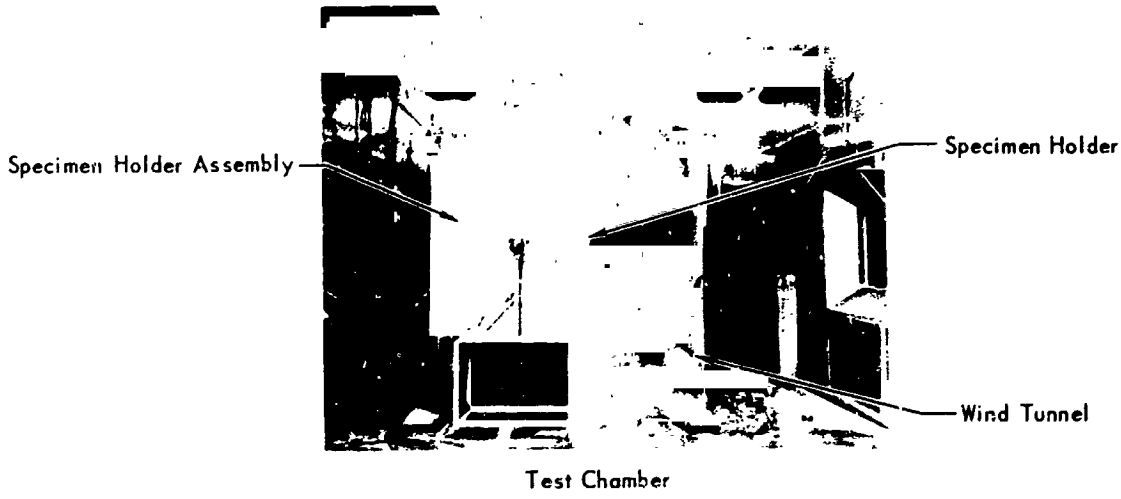


Figure 4 – Specimen Holder Assembly Mounted In Test Chamber

4.2 TEST SEQUENCE. Before the selected thermal control coatings and optical materials were subjected to the simulated Martian sand/dust erosion environment, a study of parameters associated with the sand/dust storms was conducted. The values of the parameters selected for testing were within the regime of wind velocities and static pressures listed by NASA as satisfactory Mars lander engineering model guidelines.[1] The test sequence flow chart is shown in Table 2.

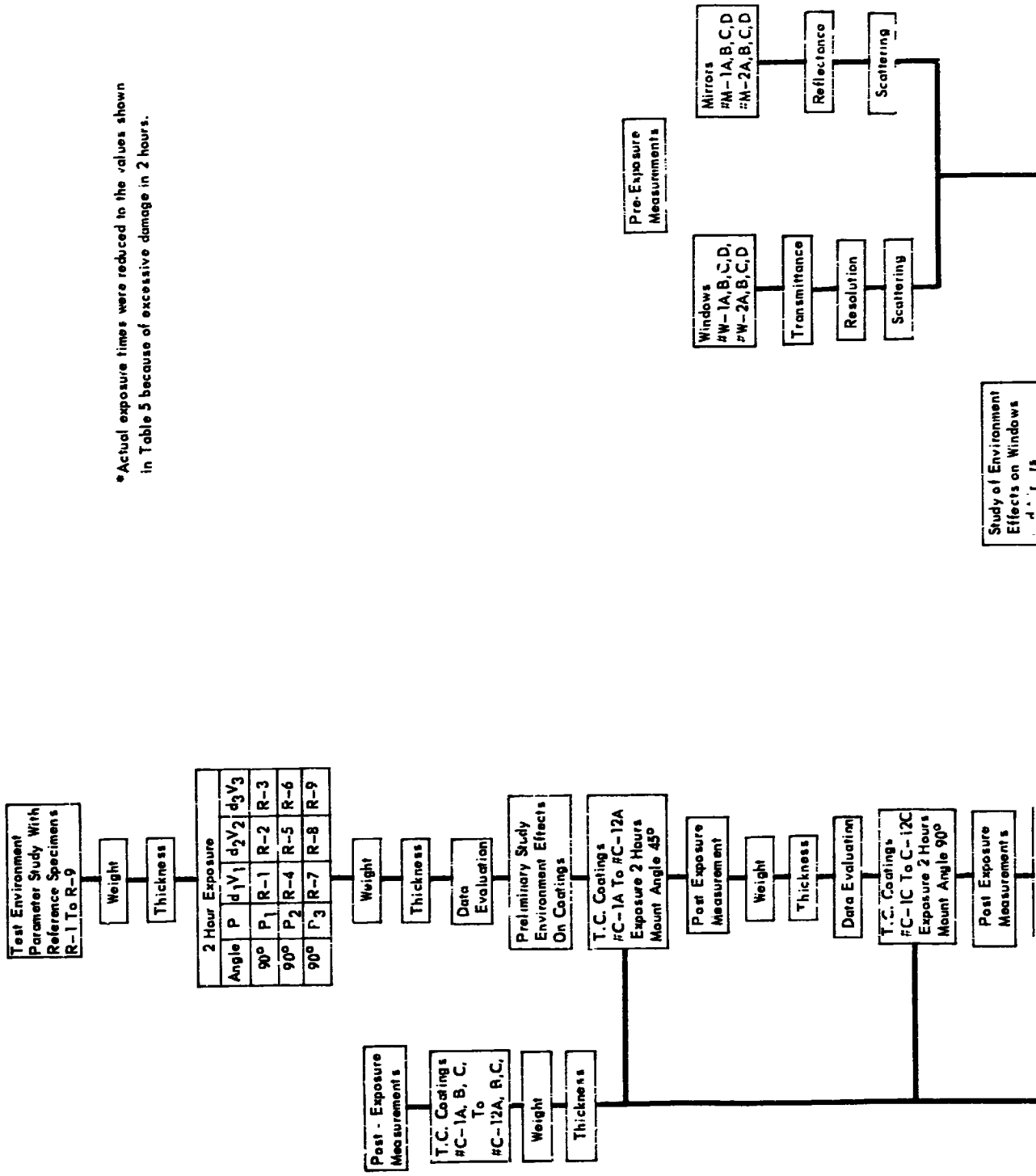
4.2.1 PARAMETER STUDY - REFERENCE SPECIMENS. Reference Specimens R-1 through R-9 were subjected to a range of test conditions within the guideline limits[1] in order to select the best single set of parameters to produce reasonable erosion of the test samples to be evaluated. The reference specimens used in the evaluation of erosion environment severity were silica glass slides, grit blasted 6061 aluminum plates, and plasma sprayed Al_2O_3 coating on 6061 aluminum. All of the 2 x 2-inch specimens were mounted with their test surfaces at an angle of 90 degrees (normal to the wind). Each reference number (R-1 through R-9) represented three slides, one of each material. The criteria used here for determining parameter severity consisted of weight and thickness measurements before and after erosion. Weight change was measured by the use of an analytical balance, and coating thickness loss was measured with a micrometer.

The conditions chosen from this series of tests and used for subsequent erosion studies were a wind speed of 220 ft/sec, static pressure of 7 torr, dust density of 1×10^{-4} oz/ft^3, and an exposure time of 2 hours. The specimen mounting angle and the dust density were varied to determine their effect upon erosion.

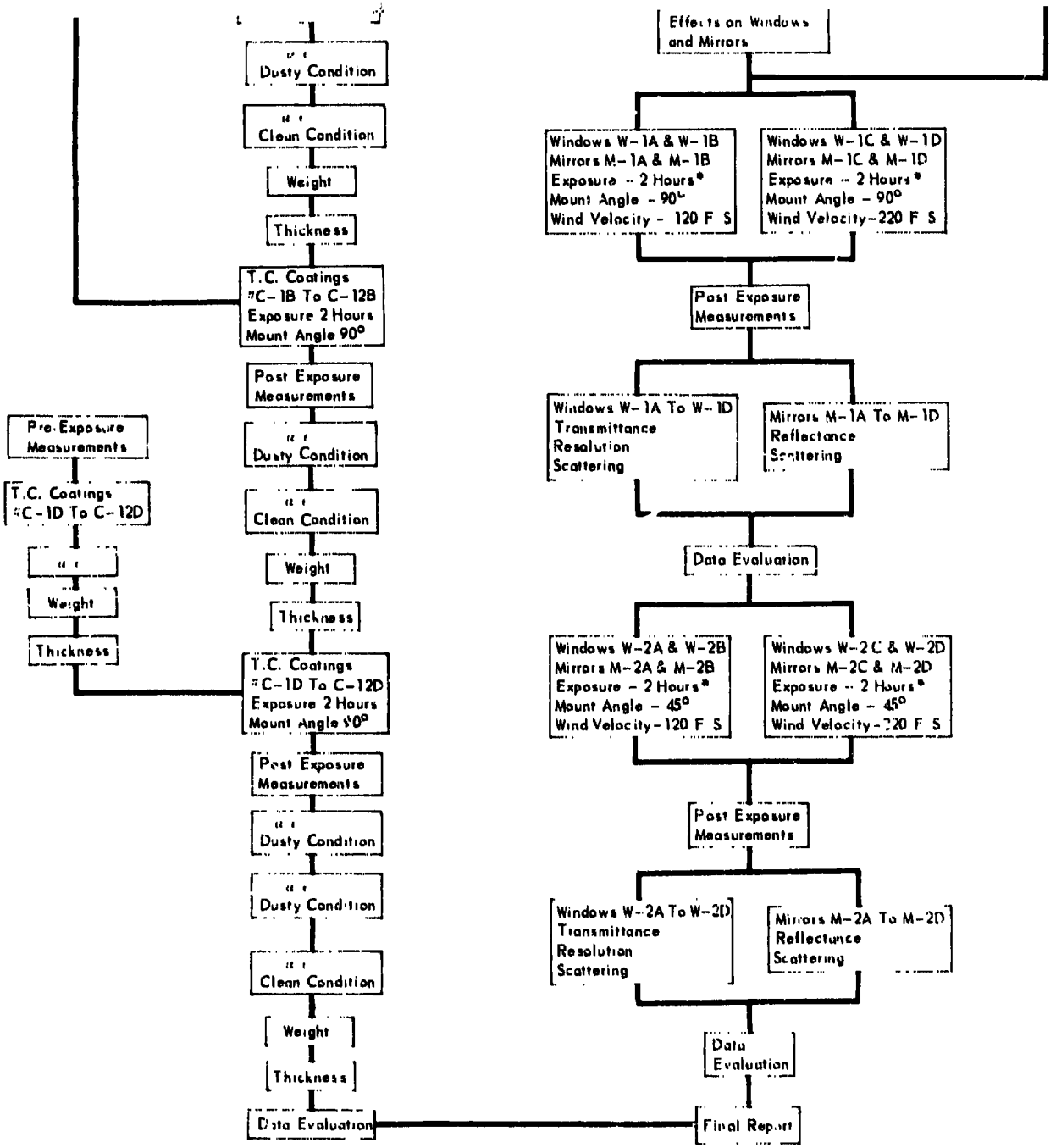
4.2.2 PARAMETER STUDY - THERMAL CONTROL COATINGS. The exposure parameters used for the erosion study of Group C-1A through C-12A were those indicated in

Table 2 Test Sequence

*Actual exposure times were reduced to the values shown in Table 5 because of excessive damage in 2 hours.



FOLDOUT FRAME



FOLDOUT FRAME 2

Paragraph 4.2.1 but at a 45-degree mounting angle. The purpose of using a 45-degree angle was to evaluate the erosion effect of particles having components of force in shear and normal to the coating face. Results of the test are shown in Tables 3 and 4. Emittance and absorptance measurements were not made for Group C-A specimens because the main interest was to confirm the selection of satisfactory erosion parameters.

4.2.3 EROSION STUDY OF THERMAL CONTROL COATINGS. Three groups of specimens (Groups C-B, C-C, and C-D) were measured for weight, thickness, total normal emittance (ϵ_T) and solar absorptance (α_S) before and after the exposure to the erosion environment. One set of α_S and ϵ_T values was obtained immediately after removal from the erosion environment while residual dust was still on the coating surfaces. Another set of values was taken after the coating surfaces were cleaned by brushing with a soft Nylon brush in a stream of nitrogen gas. Four coating specimens and a silica glass reference slide were mounted in each specimen holder as shown in Figure 4. Each glass slide served as a control specimen for verifying the severity of the erosion exposure for the group of specimens tested with it. The weight loss was determined by use of an analytical balance and the thickness measurements were made with a micrometer. A Beckman DK-2A Ratio Recording Spectrometer with an integrating sphere reflectometer was used to measure the solar absorptance at ambient temperature and pressure. A Gier Dunkle Emissometer, Model EM-2, was used to measure the infrared emittance.

4.2.4 EROSION STUDY OF OPTICAL MATERIALS. The optical materials (Groups W1A-D, W2A-D, M1A-D, and M2A-D) were mounted in the same type of specimen holder used for thermal control coatings and were first subjected to the simulated

Table 3 – Change in Coating Weight

Material	Post – Exposure Results Exposure Parameters* Group C-1A/C-12A 45° 2 Hours 1.0×10^{-4} oz Ft^3	Group C-1C/C-12C 90° 2 Hours 1.0×10^{-4} oz Ft^3	Group C-1B/C-12B 90° 2 Hours 1.45×10^{-4} oz Ft^3	Group C-1D/C-12D 90° 4 Hours 1.5×10^{-4} oz Ft^3
	ΔWt (Grams)**			
Aluminized Teflon	.00	.00	.00	.00
Gold Coated Teflon	.00	.00	.00	.00
Gold Coated Kapton	.00	.00	.00	.00
Grit Blasted 6061T6 Aluminum	.00	.00	.00	.00
Glass Resin Unpigmented	.00	.00	.00	.00
White Polyurethane	.00	.00	.00	.00
Aluminum Pigmented Silicone	.00	.00	.00	.00
Aluminum Pigmented Epoxy	−.01	−.01	−.01	−.01
Flame Sprayed NiAl	−.07	−.07	−.07	−.12
Plasma Sprayed Al_2O_3	−.08	−.15	−.19***	−.47
Flame Sprayed NiAl - ZrO_2	−.11	−.14	−.16	−.17
Alumino-Silicate Pigmented Glass Resin	−.17	−.19	−.21	−.31
Glass Slide Reference	−.01	−.04	−.04	−.09
Glass Slide Reference	−.01	−.04	−.05	−.10
Glass Slide Reference	−.01	−.04	−.05	−.12

Note: *Pressure 7.0 Torr
Wind Velocity 220 Ft/Sec
**Test Specimens Were Cleaned With Compressed Nitrogen and A Soft Nylon Brush Prior To Measurements
***Estimated

Table 4 – Change in Coating Thickness

Materials	Post Exposure Results Exposure Parameters*			
	Group C-1A C-12A	Group C-1B C-12B	Group C-1C C-12C	Group C-1D C-12D
	45° 2 Hours 1.0×10^{-4} Oz Ft^3	90° 2 Hours 1.0×10^{-4} Oz Ft^2	90° 2 Hours 1.45×10^{-4} Oz Ft^3	90° 4 Hours 1.5×10^{-4} Oz Ft^3
	Δ Thickness Mils **			
Aluminized Teflon	0	0	0	0
Glass Resin – Unpigmented	0	0	0	0
Gold Coated Kapton	0	0	0	0
Gold Coated Teflon	0	0	0	0
Grit Blasted 6061T6 Aluminum	0	–0.2	–0.2	–0.3
Aluminum Pigmented Epoxy	–0.1	–0.2	–0.3	–0.7
Aluminum Pigmented Silicone	–0.2	0	–0.1	0
White Polyurethane	–0.3	–1.0	–1.2	–0.2
Flame Sprayed NiAl	–1.0	–0.9	–1.1	–1.5
Plasma Sprayed Al_2O_3	–1.1	–1.4	–0.6	–3.6
Flame Sprayed NiAl ZrO_2	–1.2	–0.2	–0.5	–0.8
Alumino-Silicate Pigmented Glass Resin	–3.5	–3.4	–3.8	–4.6
Glass Slide Reference	0	–0.2	–0.3	–0.5
Glass Slide Reference	0	–0.2	–0.2	–0.4
Glass Slide Reference	–0.1	–0.2	–0.4	–1.1

Notes:* Pressure 7.0 Torr
Wind Velocity 220 Ft Sec
**Test Specimens Were Cleaned With Compressed Nitrogen and A Soft Nylon Brush Prior To Measurements

Table 5 – Window And Mirror Erosion Parameters

Specimens		Mounting Angle Degrees	Wind Velocity Ft/Sec	Dust Density Oz/Ft^3	Exposure Time Minutes
Windows	Mirrors				
W-1A W-2A	M-1A M-2A	90	220	1.45×10^{-4}	5
W-1B W-2B	M-1B M-2B	90	220	1.45×10^{-4}	10
W-1C W-2C	M-1C M-2C	90	220	1.45×10^{-4}	15
W-1D W-2D	M-1D M-2D	90	220	1.45×10^{-4}	20

Martian sand/dust storm conditions shown in Table 2 (1.5×10^{-4} oz/ft^3 density, 7 torr pressure, and 220 ft/sec velocity, at an angle of 90 degrees to the test sample surface, for two hours). However, the preceeding test conditions proved to be so severe that a parametric study of the effect of surface damage on optical properties was impossible. In order to establish optimum test conditions, a set of soda-lime glass samples was tested under these conditions:

$V = 220$ ft/sec

$\rho = 1.45 \times 10^{-4}$ oz/ft^3

$P = 7$ torr

$t = 5, 10, 15$ minutes

The degree of surface damage was determined by measuring the direction transmittance at a wavelength of 632.8 nm (nanometers) as described in Appendix A. The results of these measurements indicated that exposure times as small as 5 minutes caused a significant amount of surface damage. The results of this preliminary test were used to establish a more realistic set of test conditions. A new set of samples was fabricated and tested under the revised conditions shown in Table 5.

The resolution of the windows material (fused silica, alumino-silicate) were measured with the optical arrangement described in Appendix B. A variable modulation test target, manufactured by Diffraction Limited, Inc., was used to measure the resolution over a contrast range of 10 to 97.7 percent. Measurements were made visually, at ten contrast settings, before and after exposure.

Since the preliminary measurements indicated that the direction transmittance is sensitive to the degree of surface damage, it was decided to measure

both the diffuse transmittance (DT) and the diffuse plus specular transmittance (DST) over a wavelength range of 650 to 2750 nm. Both of the latter measurements were made with a Beckman DK-2A Spectrometer equipped with an integrating sphere reflectometer. The DST was measured by placing the sample in front of the sample beam entrance port on the integrating sphere (Figure 5) with magnesium oxide coated plates in both the exit reference and sample positions. This arrangement utilizes the light transmitted by the sample over a complete hemisphere. The DT was measured by removing the opposite magnesium oxide coated plate, which permitted the specular component (the normal component of the transmitted flux) to leave the integrating sphere exit port. In this case only the scattered light incident on the wall of the integrating sphere is utilized for the measurement. One hundred percent and zero lines were established on the spectrometer chart by comparing two identical smoked magnesium oxide plates.

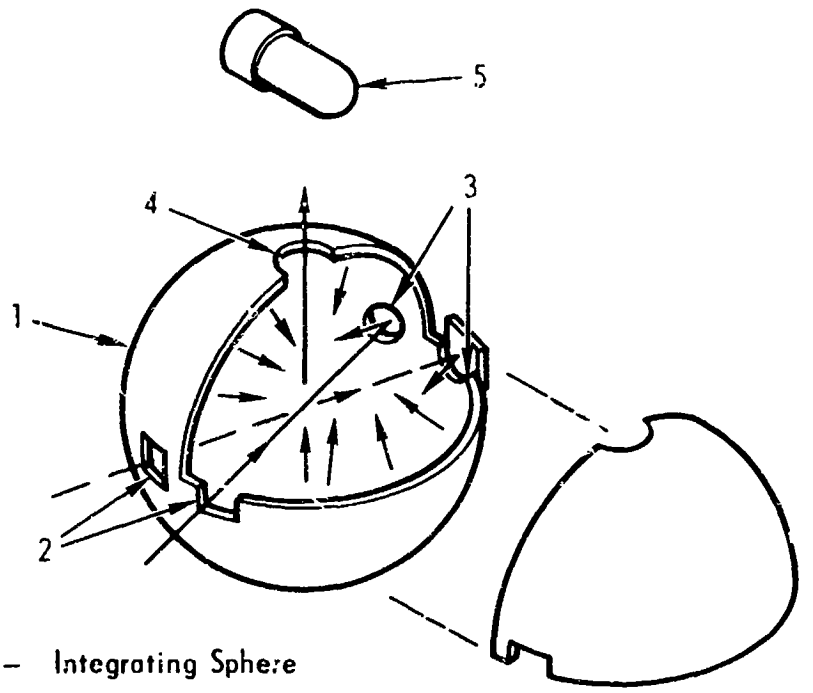
Reflectance measurements on the mirrors were made with the sample replacing the magnesium oxide plate in the sample beam. Measurements were made on the mirrors before and after exposure to the simulated Martian dust storms.

Scattering of light by the mirrors was measured by positioning the mirror in the sample exit port so that the beam was reflected back on itself, and out the port. Only the light scattered out of the reflected beam and incident on the wall of the integrating sphere is detected with this technique.

4.3 EROSION TEST RESULTS

4.3.1 COATINGS

4.3.1.1 WEIGHT CHANGE. Exposure to the erosion environment did not cause detectable weight loss from the tough coatings (Teflon, Kapton, silicone, polyurethane, etc.). The hard surfaces (flame sprayed nickel aluminide (NiAl),



1– Integrating Sphere

2– Entrance Ports (Samples Are Placed Here For Absorptance and Transmittance Measurements)

3– Exit Ports (Sample and Reference Materials Are Placed Here For Reflectance and Fluorescence Measurements; Otherwise, Ports Are Normally Covered With Magnesium Oxide Plates)

4– Integrating Sphere Opening (Filter Is Placed Here For Fluorescence Measurements)

5– Detector

Figure 5 – Integrating Sphere Reflectometer Optical Arrangement

plasma sprayed Al_2O_3 and glass reference slides) and the soft highly pigmented H-10 coating did experience significant weight losses.

At a given dust density and wind velocity, change in orientation from 45 to 90 degrees had no appreciable effect on weight loss except for the Al_2O_3 and the glass reference slides. Both of these materials had a higher weight loss at a 90-degree angle. The H-10 and flame sprayed NiAl + ZrO_2 both experienced only slight differences in weight loss due to changing the angle.

Increasing the dust density from 1.0×10^{-4} to 1.45×10^{-4} oz/ft^3, with a 90 degree angle, did not cause an appreciable increase in the weight loss of any materials tested.

Increasing the exposure time from 2 to 4 hours, with approximately the same dust density (1.5×10^{-4} oz/ft^3) and a 90 degree angle, did increase the weight loss for the flame and plasma sprayed coatings and the soft H-10 coating. Except for the glass reference materials, increasing from a 2-hour exposure to a 4-hour exposure did not double the weight loss from the hard materials.

4.3.1.2 THICKNESS CHANGE. The weight and thickness loss from the glass reference slides might be expected to be directly proportional. The lack of precise correspondence in the data of Table 4 is attributed to factors such as adherence of dust coatings, and chipping or pitting in the case of glass slides. Separation of coatings from their substrates, surface spalling causing isolated thickness increases, etc., result in local variations in thickness which may not correspond directly with weight changes.

Resilient coatings, such as those made of Kapton or Teflon were not eroded by the sand/dust exposure. The hard coatings were eroded rather severely, but this factor has the compensating advantage of exposing clean thermal control

surface material. The α_S/ϵ_T ratios for erodible surfaces therefore tend to remain at their original values, as long as a reasonable amount of the coating thickness remains.

4.3.1.3 EMITTANCE AND SOLAR ABSORPTANCE CHANGE. The consistency of α_S, ϵ_T, and α_S/ϵ_T data shown in Tables 6, 7, and 8 is quite good considering that only one specimen of each coating type was exposed to any one parameter. The first column in each table contains the average values of clean and unexposed specimens of each coating type. These average values were determined from the four specimens of each coating type used in the tests. The values in the other columns are for individual specimens.

Resilient coatings such as aluminized Teflon, gold coated Kapton, gold coated Teflon, and polyurethane did not lose coating material in the erosion environment, but dust adhered to or became embedded in the coatings and caused the α_S/ϵ_T values to increase with exposure time, as shown in Table 8.

Hard coatings (plasma sprayed Al_2O_3, flame sprayed NiAl, and NiAl + ZrO_2) lost some of their coating thickness, but erosion reduced the buildup of a contaminating dust film. The α_S/ϵ_T ratios shown in Table 8 for the plasma sprayed Al_2O_3 and the alumino-silicate pigmented glass resin (H-10) coatings remained relatively stable despite the severity of the erosion parameters. The α_S/ϵ_T ratio for unpigmented glass resin also stablized, but its value was somewhat higher.

At one time, the aluminized Teflon had been considered for the radiator of the Viking Mars lander. This coating has an initial α_S/ϵ_T value of 0.308. Surface erosion raised the value to 0.862 after 4 hours (Table 8). No coating loss was measured, so the α_S/ϵ_T increase was probably caused by surface roughening, augmented by adherence of dust.

Table 6 – Change in Solar Absorptance

Material	α_s Avg.	Post Exposure Results: Group C-1C/C-12C, 2 Hours, 1.0×10^{-4} Oz Ft^3		Group C-1B/C-12B, 2 Hours, 1.45×10^{-4} Oz Ft^3		Group C-1D/C-12D, 4 Hours, 1.50×10^{-4} Oz Ft^3	
		α_s Dusty	α_s Clean**	α_s Dusty	α_s Clean**	α_s Dusty	α_s Clean**
Alumino-Silicate Pigmented Glass Resin	0.16	0.27	0.24	0.41	0.30	0.39	0.32
Aluminized Teflon	0.24	0.45	0.46	0.53	0.51	0.67	0.65
Plasma Sprayed Al_2O_3	0.27	0.34	0.33	0.41	0.39	0.46	0.41
Glass Resin – Unpigmented	0.33	0.44	0.43	0.49	0.46	0.50	0.49
White Polyurethane	0.33	0.55	0.55	0.69	0.63	0.72	0.68
Gold Coated Teflon	0.41	0.57	0.55	0.62	0.60	0.71	0.67
Gold Coated Kapton	0.51	0.73	0.72	0.80	0.79	0.86	0.82
Aluminum Pigmented Silicone	0.51	0.78	0.76	0.80	0.79	0.85	0.84
Aluminum Pigmented Epoxy	0.52	0.76	0.76	0.81	0.81	0.84	0.84
Grit Blasted 6061T6 Aluminum	0.68	0.65	0.66	0.69	0.70	0.72	0.72
Flame Sprayed NiAl - ZrO_2	0.84	0.78	0.78	0.80	0.80	0.79	0.79
Flame Sprayed NiAl	0.86	0.78	0.78	0.79	0.79	0.78	0.77

Notes * Pressure 7.0 Torr
Gas Velocity 220 Ft Sec
Specimens Mounted at 90°

**Test Specimens Were Cleaned With Compressed Nitrogen and A Soft Nylon Brush Prior To Measurements

Table 7 – Change in Emittance

Material	ϵ_T Avg.	Post Exposure Results — Exposure Parameters* — Group C-1C/C-12C — 2 Hours 1.0×10^{-4} Oz FT^3 — ϵ_T Dusty	ϵ_T** Clean	Group C-1B/C-12B — 2 Hours 1.45×10^{-4} Oz Ft^3 — ϵ_T Dusty	ϵ_T** Clean	Group C-1D C-12D — 4 Hours 1.5×10^{-4} Oz Ft^3 — ϵ_T Dusty	ϵ_T** Clean
Grit Blasted 6061T6 Aluminum	0.25	Not Measured	0.36	0.40	0.41	0.43	0.43
Aluminum Pigmented Silicone	0.44		0.71	0.72	0.71	0.72	0.72
Aluminum Pigmented Epoxy	0.47		0.67	0.71	0.68	0.79	0.74
Flame Sprayed NiAl	0.58		0.45	0.49	0.47	0.51	0.47
Flame Sprayed NiAl · ZrO_2	0.62		0.46	0.50	0.48	0.51	0.47
Gold Coated Teflon	0.65		0.66	0.65	0.67	0.70	0.69
Glass Resin – Unpigmented	0.75		0.66	0.76	0.75	0.79	0.77
Aluminized Teflon	0.77		0.76	0.77	0.76	0.79	0.75
Gold Coated Kapton	0.82		0.83	0.84	0.83	0.83	0.85
Plasma Sprayed Al_2O_3	0.83		0.83	0.83	0.83	0.86	0.86
White Polyurethane	0.89		0.85	0.90	0.89	0.91	0.92
Alumino-Silicate Pigmented Glass Resin	0.93		0.93	0.93	0.91	0.90	0.93

Notes * Pressure 7.0 Torr
Wind Velocity 220 Ft Sec
Specimen Mounted at 90°

**Test Specimens Were Cleaned With Compressed Nitrogen and A Soft Nylon Brush Prior To Measurements

Table 8 – Changes in Solar Absorptance to Emittance Ratio

Material	Avg. α_s/ϵ_T	Post Exposure Results: Exposure Parameters* Group C-1C/C-12C, 2 Hours 1.0×10^{-4} Oz Ft^3: α_s/ϵ_T Dusty	Group C-1C/C-12C, 2 Hours 1.0×10^{-4} Oz Ft^3: α_s/ϵ_T ** Clean	Group C-1B/C-12B, 2 Hours 1.45×10^{-4} Oz Ft^3: α_s/ϵ_T Dusty	Group C-1B/C-12B, 2 Hours 1.45×10^{-4} Oz Ft^3: α_s/ϵ_T ** Clean	Group C-1D/C-12D, 4 Hours 1.5×10^{-4} Oz Ft^3: α_s/ϵ_T Dusty	Group C-1D/C-12D, 4 Hours 1.5×10^{-4} Oz Ft^3: α_s/ϵ_T ** Clean
Alumino-Silicate Pigmented Glass Resin	0.172		0.260	0.441	0.334	0.427	0.341
Aluminized Teflon	0.308		0.600	0.690	0.665	0.847	0.862
Plasma Sprayed Al_2O_3	0.320		0.398	0.493	0.468	0.539	0.473
White Polyurethane	0.377		0.656	0.769	0.708	0.793	0.734
Glass Resin Unpigmented	0.422		0.654	0.645	0.618	0.636	0.646
Gold Coated Kapton	0.623		0.865	0.949	0.949	1.040	0.968
Gold Coated Teflon	0.629		0.838	0.960	0.900	1.010	0.976
Aluminum Pigmented Epoxy	1.100	Not	1.140	1.150	1.200	1.080	1.130
Aluminum Pigmented Silicone	1.150	Measured	1.080	1.120	1.120	1.180	1.170
Flame Sprayed NiAl - ZrO_2	1.360		1.700	1.590	1.690	1.550	1.670
Flame Sprayed NiAl	1.480		1.740	1.610	1.690	1.520	1.650
Grit Blasted 6061T6 Aluminum	2.760		1.810	1.730	1.720	1.690	1.680

Notes: * Pressure 7.0 Torr
Wind Velocity 220 Ft Sec
Specimens Mounted at 90°

**Test Specimens Were Cleaned With Compressed Nitrogen and A Soft Nylon Brush Prior To Measurements

The two aluminum pigmented coatings (epoxy and silicone [illegible] severely when exposed to the sand/dust erosion environment. [illegible] was not completely removed by the cleaning technique previously described. Both the α_S and the ϵ_T increased under all test conditions. A typical change for both of these coatings was an increase in α_S from 0.51 to 0.84 and an increase in ϵ_T from 0.45 to 0.75 after 4 hours of exposure at a sand/dust density of 1.5×10^{-4} oz/ft^3.

The grit blasted aluminum (6061-T6 alloy) maintained a fairly constant α_S value, varying from an initial value of 0.68 to its highest value of 0.72 after 4 hours of exposure. The ϵ_T increased from an initial value of 0.25 to an almost constant value of 0.41 for all test conditions. Exposure to the sand/dust erosion environment darkened the surface and gave it a smoother appearance.

The test results show the performance of different coating binders and indicate that additional erosion studies should be performed on any new candidate materials when α_S and ϵ_T requirements have been established for the Mars Viking lander. It was also noted that emittance values do not change as drastically as absorptance values during erosion, and erodible coatings tend to remain clean, thus retaining approximately their original α_S/ϵ_T ratios.

4.3.2 OPTICAL MATERIALS. The resolution, transmittance, and reflectance of the selected window and mirror materials were measured prior to and after exposure to the simulated Martian sand/dust storm environment. The results of the resolution measurements are given in Tables 9 and 10.

There was essentially no change in resolution for windows exposed to the simulated dust storm conditions for 5 minutes. After 10 minutes exposure,

Table 9
Fused Silica Window Resolution

Exposure Time Minutes	Contrast Percent	Resolution Before Exposure Set Number	Resolution After Exposure Set Number*
0	10	5	NA
	20	6	NA
	30	6	NA
	40	6	NA
	50	6	NA
	60	7	NA
	70	7	NA
	80	7	NA
	90	7	NA
	97.7	7	NA
5	10	5	5
	20	6	6
	30	6	6
	40	7	7
	50	7	7
	60	7	7
	70	7	7
	80	7	7
	90	7	7
	97.7	7	7
10	10	5	1
	20	6	5
	30	6	5
	40	6	6
	50	7	6
	60	7	6
	70	7	6
	80	7	6
	90	7	6
	97.7	7	6
15	10	5	0
	20	6	2
	30	6-	3
	40	7-	4
	50	7-	5
	60	7	5
	70	7	5
	80	7	5
	90	7	5
	97.7	7	5
20	10	4	0
	20	6	0
	30	6	9*
	40	7-	9*
	50	7-	9*
	60	7	1
	70	7	2
	80	7	2
	90	7	2
	97.7	7	3

*Group I Lines. All Other Set Numbers are for Group II Lines.

Table 10
Alumino-Silicate Window Resolution

Exposure Time (Minutes)	Contrast (Percent)	Resolution Before Exposure (Set Number)	Resolution After Exposure (Set Number)
0	10	6	NA
	20	6	NA
	30	6	NA
	40	7	NA
	50	7	NA
	60	7	NA
	70	7	NA
	80	7	NA
	90	7	NA
	97.7	7	NA
5	10	5	4
	20	6	6
	30	6	6
	40	7	6
	50	7	6
	60	7	7
	70	7	7
	80	7	7
	97.7	7	7
10	10	5	4
	20	6	5
	30	6	6
	40	6	6
	50	7	6
	60	7	6
	70	7	6
	80	7	6
	90	7	7
	97.7	7	7
15	10	4	1
	20	5	4
	30	6	5
	40	6	5
	50	7	5
	60	7	6
	70	7	6
	80	7	6
	90	7	6
	97.7	7	6
20	10	6	0
	20	6	1
	30	6	2
	40	6	3
	50	7	3
	60	7	4
	70	7	4
	80	7	4
	90	7	5
	97.7	7	5

All Set Numbers in this Table are for Group II Lines.

resolution decreased about 1 set number. After 15 minutes exposure, resolution decreased about 2 set numbers at 50 percent contrast, but dropped off more rapidly at lower contrast values, especially for fused silica. After 20 minutes exposure, the decrease in resolution at 50 percent contrast was 9 set numbers for fused silica, and 4 for alumino-silicate. There was no resolution for fused silica at or below 20 percent contrast, or for alumino-silicate at 10 percent contrast.

For samples exposed 15 or 20 minutes the image of the resolution target was quite dark, making readings difficult. This darkening is in agreement with the curves of transmittance vs exposure time, at 550 nm as shown in Figure 6. The difference between the upper curve (diffuse plus specular transmittance), and the lower curve (diffuse transmittance), is the amount of incident light usable to form an image. For samples exposed 15 minutes or more, less than 15 percent of the incident light reaches the image. The initial test data, Figure 6, indicated that the harder alumino-silicate is a better window material than the fused silica for the sand/dust erosion environment. The alumino-silicate has a Knoop hardness (100 gm load) of 595 Kg/mm^2 as compared to a Knoop hardness (100 gm load) of 560 Kg/mm^2 for fused silica. After 5 minutes of exposure, the difference between the diffuse plus specular and the diffuse transmittance for the alumino-silicate is 56 percent, as compared to 46 percent for the fused silica material.

No resolution measurements were made on the mirrors. If the mirror reflectance and scattering for Figures 7 and 8 are interpreted in the same manner as for window transmittance, it is evident that very little light is available for formation of an image. The mirrors are slightly less degraded in the infrared (1750 nm) than in the visible region (550 nm). The second

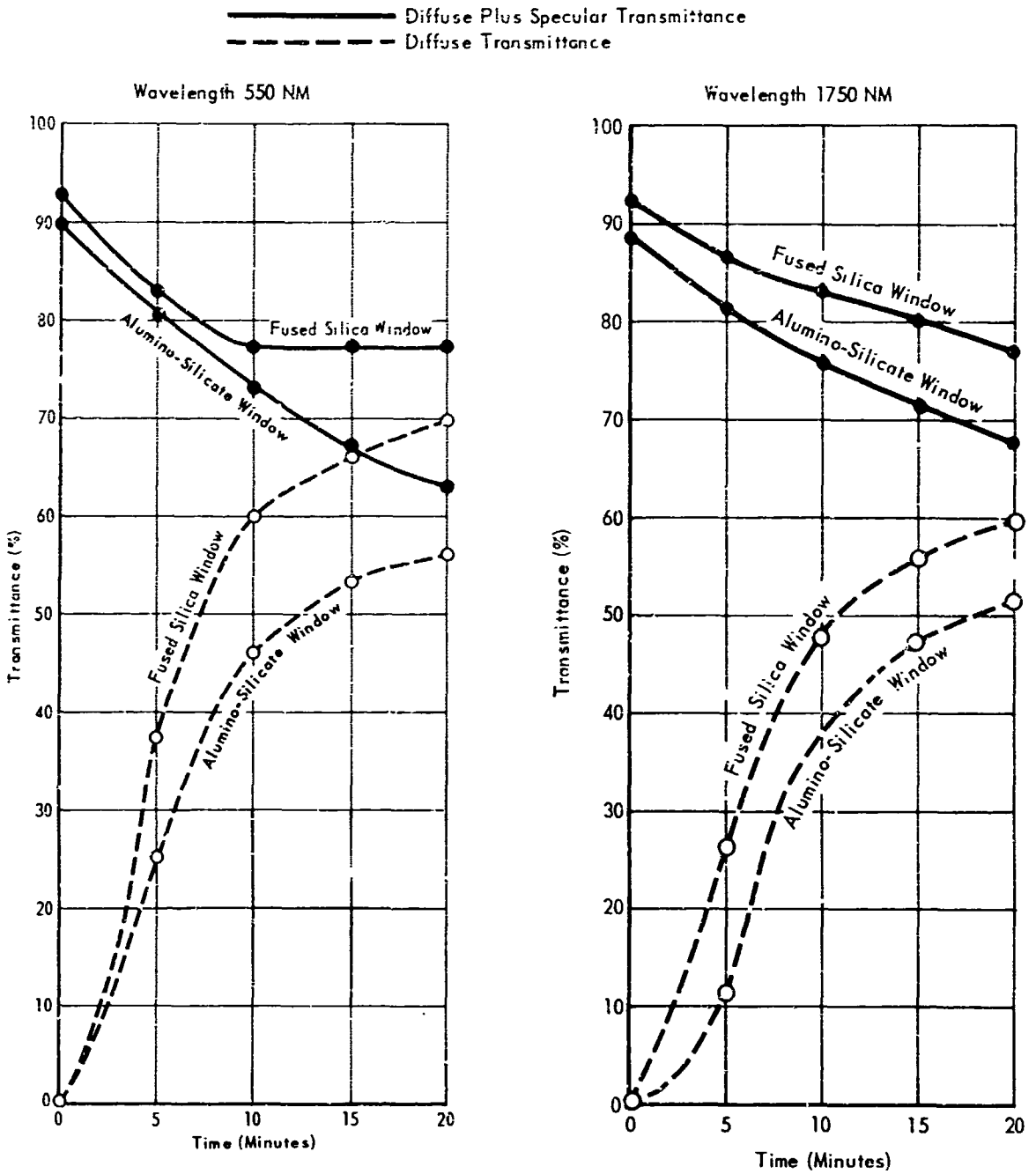


Figure 6 – Transmittance Vs Exposure Time for Windows

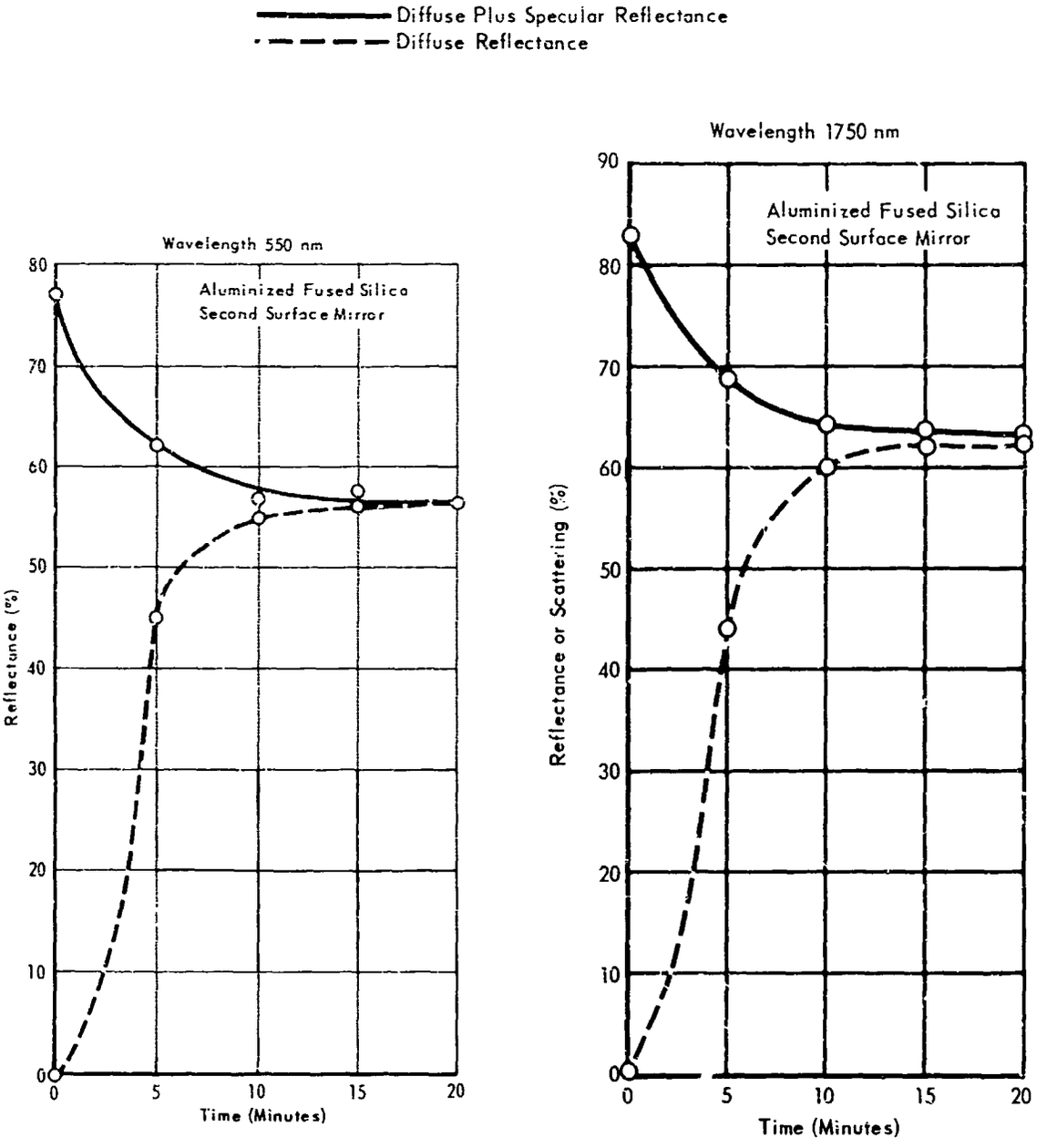


Figure 7 – Reflectance vs Exposure Time for Second Surface Mirror

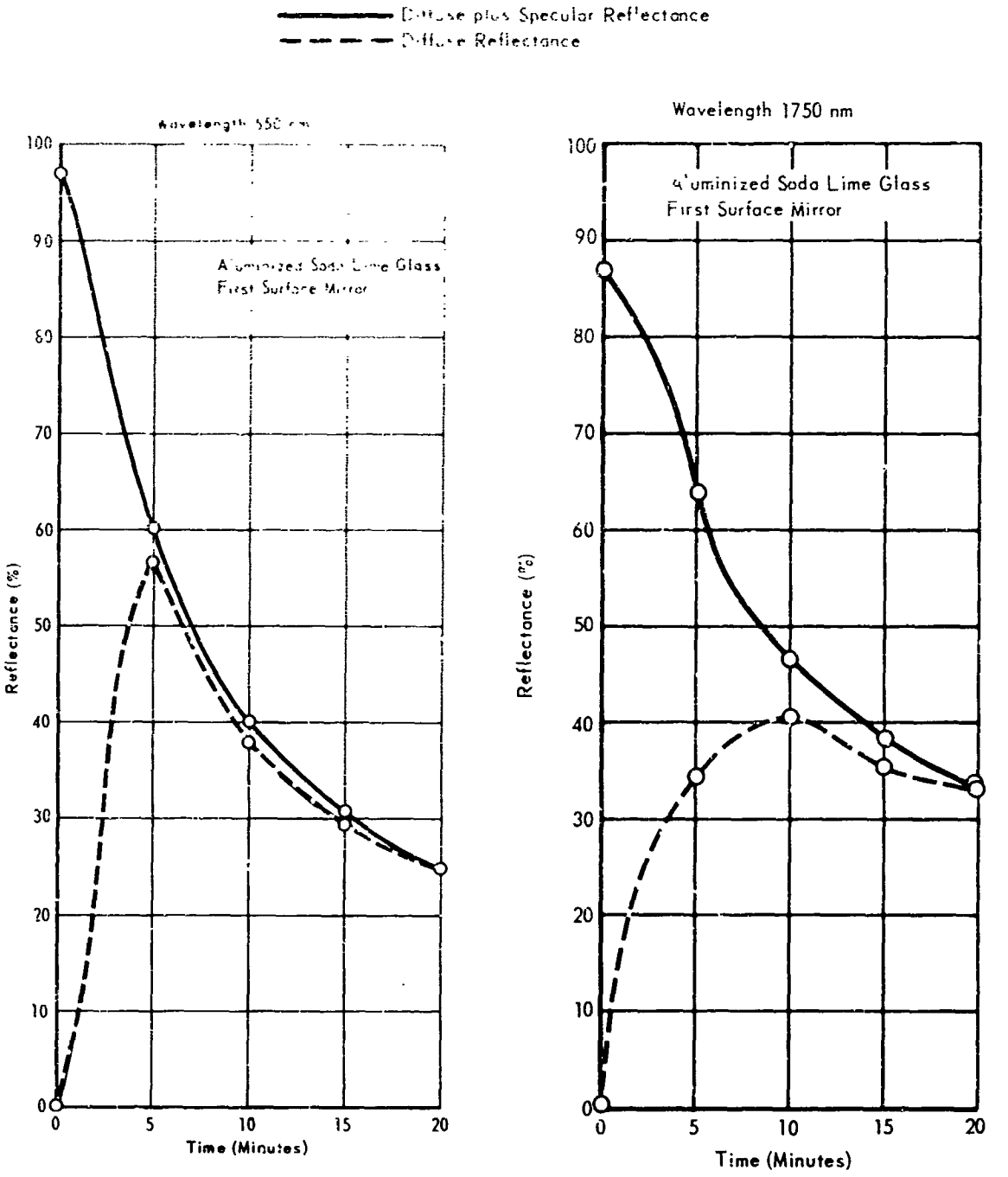


Figure 8 – Reflectance vs Exposure Time for First Surface Mirror

surface mirrors were physically more durable than the first surface mirrors, but it should be noted that incident light passes through the damaged front surface of a second surface mirror twice.

5. DISCUSSION

The erosion of the hard materials (flame sprayed coatings and the glass reference specimens) increased as exposure time and dust density were increased. The more resilient coatings such as Teflon, Kapton, polyurethane, elastomeric silicone, etc., did not exhibit weight loss under any test conditions.

Erosion caused large increases in solar absorptance by all coatings except the flame-sprayed nickel aluminide-type coatings. All coatings exhibited increases in solar absorptance due to dust pickup and/or changes in surface roughness.

The nickel aluminide-type coatings were the only ones to exhibit a decrease in infrared thermal emittance as a result of exposure to the sand/dust erosion environment. All other coatings exhibited increased emittance values or showed no change in emittance. Consequently, even though most of the coatings exhibited an increase in α_S, the α_S/ϵ_T ratio for a number of them remained in the useful range from 0.40 to 0.70.

The specimens with initially lower absorptance to emittance ratios (H-10 and plasma-sprayed Al_2O_3) had the smallest changes in their ratios. The H-10 and plasma-sprayed Al_2O_3 eroded away and always presented a relatively clean dust-free surface. The more resilient surfaces tended to become coated with silica dust which obscured the original surfaces. Some of the white coatings were observed to darken somewhat during simulated sand/dust storms. This grayish discoloration was examined microscopically (at a magnification of 200), by infrared multiple internal reflection spectrophotometry, and by emission spectrographic analysis. Scrapings and solvent washings from portions of the

surfaces were analyzed by infrared transmission techniques. Within the limits of sensitivity of these techniques, the only surface contaminant detected was silicon oxide from a very thin layer of embedded silica dust. Aqua regia washings of some of the surfaces were analyzed by emission spectroscopy and were found to contain some aluminum with lesser amounts of iron and chromium and traces of zinc, nickel, lead, and manganese. It is possible that these metals were impurities on the dust particles embedded in the coating surfaces and that the impurities had been abraded from the aluminum wind tunnel, stainless steel disperser, and steel air supply piping.

The solar constant for Mars is 190/Btu/hr/ft^2 (less than one-half that for Earth). A coating with an α_S/ϵ_T ratio of approximately 0.70 (with $\epsilon_T = 0.80$) could possibly be utilized on a lander without having the vehicle overheat due to sand/dust storm exposure on the Martian surface. The results of this study indicate that further tests would be useful in selecting suitable thermal control coatings for a Mars lander.

The test results indicate that for window materials exposed longer than 10 minutes and mirrors exposed longer than 5 minutes the amount of radiation available for image formation is significantly decreased. This results in a serious loss in resolution, especially at low contrast levels. The brightness of an image, as observed with a first surface mirror was less than 10 percent of the true brightness. For windows exposed longer than 10 minutes, the brightness was less than 15 percent in the visible (550 nm) and less than 25 percent in the infrared (1750 nm) regions.

APPENDIX A

DIRECTIONAL TRANSMITTANCE OF SAMPLES EXPOSED TO SIMULATED MARTIAN SAND/DUST STORM CONDITIONS

by T. H. Allen

The directional transmittance is not only a function of the intrinsic optical properties (e.g. refractive index and absorption constant) but also geometrical factors. These geometrical factors include microscopic surface imperfections and gross surface curvature. Of primary interest is the fact that the directional transmittance can be used as a measure of surface damage that could be caused by exposure to Martian sand/dust storm conditions. In order to determine the feasibility of this technique the directional transmittance of three glass samples was measured after exposure to simulated Martian sand/dust storm conditions.

The basic instrument consists of a divided circle spectrometer modified to permit focusing radiation on the sample, as shown in Figure A-1. The source was a helium-neon laser with an output of 0.001 watt at a wavelength of 632.8 nm. The radiation transmitted by the sample was collected and subsequently focused on a diffuser ahead of a photomultiplier (RCA8571). The collection optics and detector are mounted on a support which can be rotated with respect to the sample.

The measured directional transmittance over an angular interval of 0 to 70 degrees is shown in Figure A-2. The sand/dust particulate velocity and density were the same for all three samples, but the exposure times were varied from 5 to 15 minutes. These measurements clearly indicate that the directional transmittance is sensitive to this type of surface damage and that significant damage occurred during exposure times of as little as 5 minutes under these test conditions.

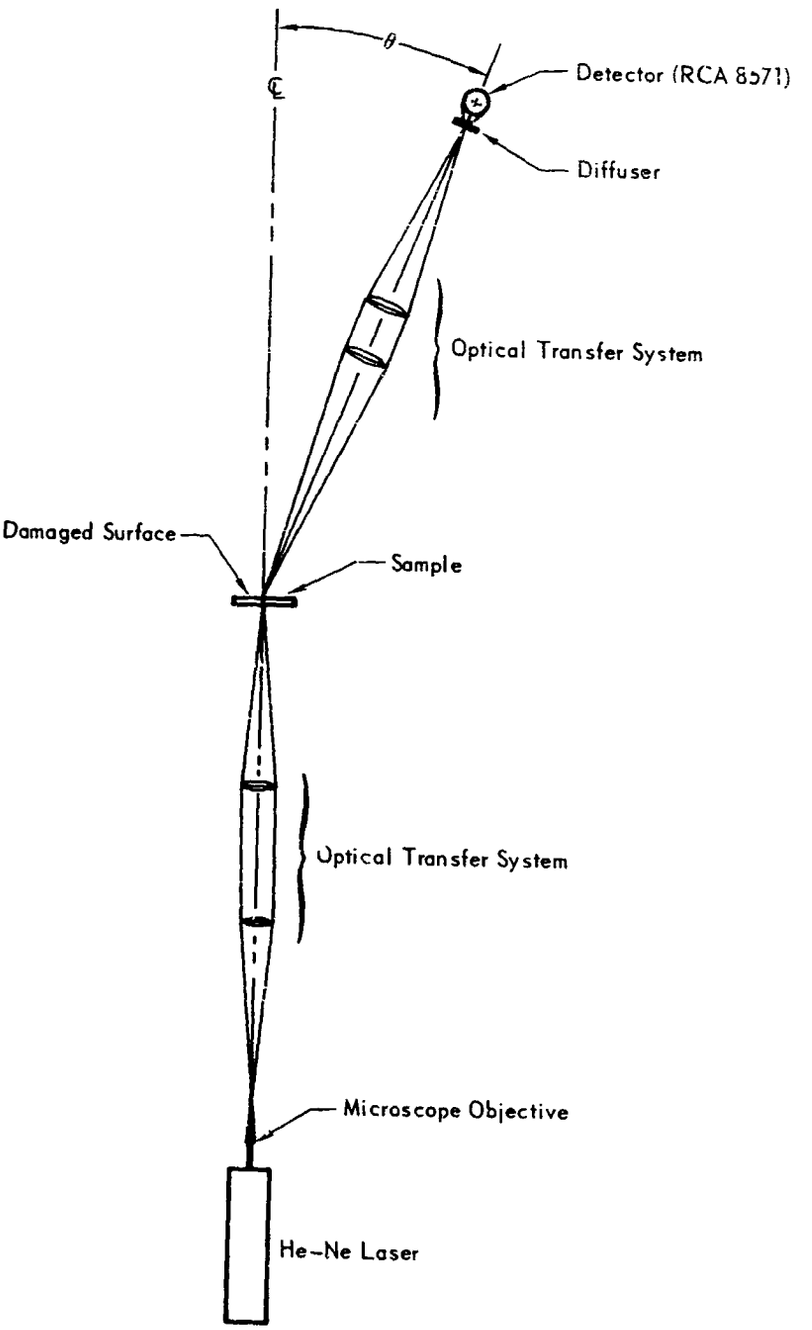


Figure A–1 – Optical Arrangement

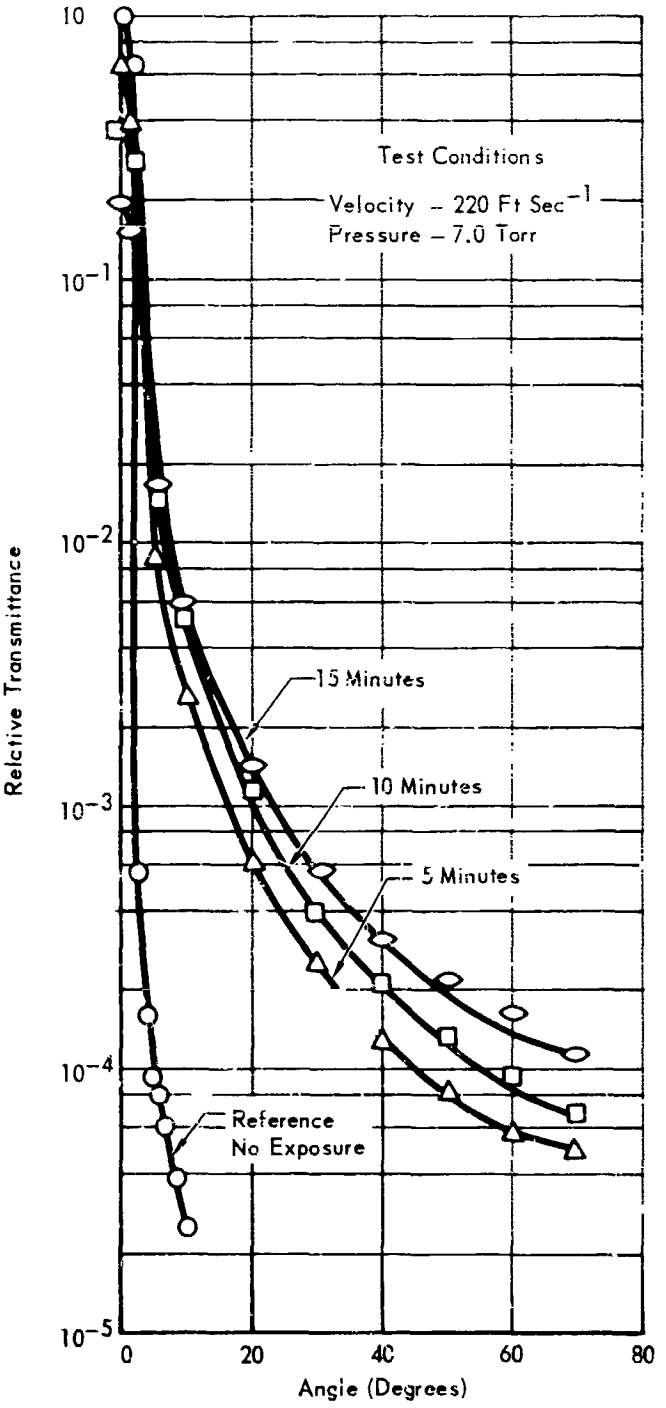


Figure A--2 – Effect of Exposure on Directional Transmittance

APPENDIX B

RESOLUTION OF OPTICAL MATERIALS
by T. H. Allen

Resolution, as used in these reported measurements, is the measure of the maximum number of lines per millimeter (spacial frequency) which can be distinguished. The target has a range of spacial frequencies ranging from 1 to 1000 cycles per millimeter. In addition, the contrast can be varied from 10 to 97 percent. The contrast, C, is defined by the equation:

$$C_1 = \frac{B_1 - B_2}{B_1}$$

where B_1 is the luminance of the spaces and B_2 the luminance of the bars of the target. The measurements are recorded in terms of sets where each set has the following spacial frequency:

SET NO.	SPACIAL FREQUENCY (mm^{-1})
1	57.17
2	74.49
3	93.78
4	118.09
5	148.63
6	187.15
7	235.60

The optical arrangement used for making the resolution measurements consisted of a f/16 collimator having a focal length of 79 inches and an imaging f/5.6 lens with a focal length of 12 inches. The sample was placed approximately 99 inches in front of the collimator, as shown in Figure B-1, and the resulting image was examined with a microscope having a magnification of 20 times.

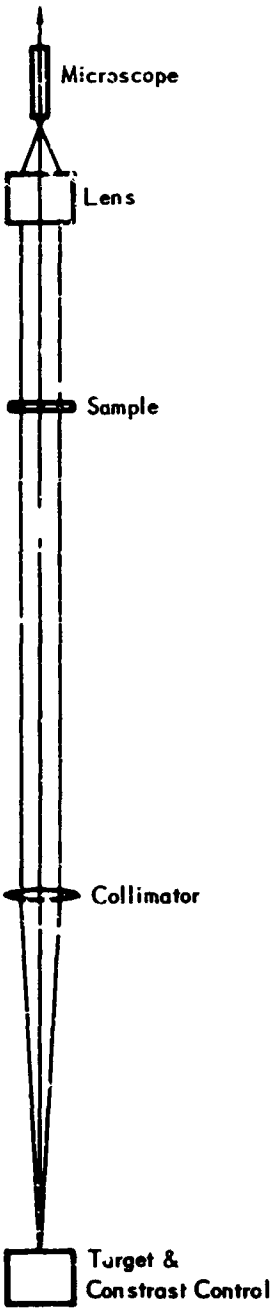


Figure B–1 – Optical Arrangement

APPENDIX C

REFERENCES

1. Langley Research Center, "Mars Engineering Model Parameters for Mission and Design Studies," May 1968.

2. Hertzler, R. G., "Behavior Characteristics of Simulated Martian Sand and Dust Storms," McDonnell Aircraft Co., Report E720, 25 August 1966.

3. Stone, Irving, "Atmospheric Data to Alter Voyager Design," Aviation Week and Space Technology, 22 November 1965.

4. de Wys, E. Christian, "The Surface of Mars," (Prepared by JPL in 1968 for NASA).

5. Ryan, J. A., "Notes on the Yellow Clouds," Journal of Geophysical Research, 15 September 1964, Vol. 69.

6. Rusert, E. L. and Wilbers, C. J., "Effects of Spacecraft Sterilization Procedures and Mars Environment on Thermal Control Coatings" SAMPE Eleventh National Symposium, April 1967, St. Louis, Mo.

PLANETARY ENVIRONMENT SIMULATION
Erosion And Dust Coating Effects

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IV. NASA CR-66878

ABSTRACT

Ten thermal coatings, two mirrors and two window materials, for application on the 1973 Mars Viking Lander vehicles, were exposed to simulated Martian surface conditions. Weight, thickness, solar absorptance, infrared emittance, reflectance, and transmission changes were measured on the samples exposed to two different dust densities at 45 and 90 degree angles to the flow and exposure times of 2 and 4 hours. After 10 minutes of exposure, the fused silica and the alumino-silicate window materials were rendered unusable as a transmitting material. Large increases in solar absorptance were measured for most of the coatings exposed to the simulated environment. Although these coatings exhibited this increase in solar absorptance, the α_S/ϵ_T ratio for a number of these coatings remained in the useful range of 0.40 to 0.70.